*Report No. 5*
*Fifth Quarterly Report*

*Covering the Period*
*1 September 1964 to 30 November 1964*

# Investigation of MICROWAVE DIELECTRIC-RESONATOR FILTERS

*Prepared for:*
U. S. ARMY ELECTRONICS LABORATORIES
FORT MONMOUTH, NEW JERSEY

CONTRACT DA 36-039-AMC-02267(E)
TASK NO. 5544-PM-63-91

*By: S. B. Cohn and E. N. Torgow*



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RANTEC CORPORATION
CALABASAS, CALIFORNIA

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*Rantec Project No. 31625*

*Approved:*

Seymour B. Cohn

SEYMOUR B. COHN, Technical Director

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## SECTION I

## PURPOSE

This program is intended to study the feasibility of high-dielectric-constant materials as resonators in microwave filters, and to obtain design information for such filters. Resonator materials shall be selected that have loss tangents capable of yielding unloaded Q values comparable to that of waveguide cavities. The materials shall have dielectric constants of at least 75 in order that substantial size reductions can be achieved compared to the dimensions of waveguide filters having the same electrical performance.

## SECTION II

## ABSTRACT

The use of dielectric resonators in band-stop filters is discussed. The most promising application is in TEM transmission-line structures. The coupling between a dielectric resonator and a propagating TEM line is studied. Formulas are derived which, to an accuracy adequate for most applications, predict the external Q ($Q_{ex}$) of the coupled resonator as a function of the resonator's parameters and its position in the transmission-line cross section.

Application of the $Q_{ex}$ formulas to band-stop filter design is investigated. A formula is presented expressing the required $Q_{ex}$ values of the resonators in terms of the elements of a low-pass-prototype filter. Several band-stop filters were designed and tested. Agreement between measured and theoretical performance is excellent.

Additional dielectric samples supplied by U. S. Army Electronics Laboratories have been measured in the radial-line dielectrometer. Among the samples tested are several that are significantly more dense than earlier samples. These dense samples exhibited dielectric constants as high as 113. Q and temperature stability of these samples were also measured. The quality of these samples from the point of view of Q was found to be comparable to the samples tested previously.

## SECTION III

## CONFERENCES AND PUBLICATIONS

A conference was held at Rantec Corporation on 30 September and 1 October 1964. Mr. E. A. Mariani of U.S. Army Electronics Laboratories and Dr. S. B. Cohn and Mr. E. N. Torgow of Rantec Corporation attended. Progress during the fourth quarter and plans for the fifth quarter were reviewed.

A paper entitled, "Microwave Filters Containing High-Q Dielectric Resonators," by Dr. Seymour B. Cohn has been accepted for presentation at the 1965 G-MTT Symposium.

## SECTION IV

## FACTUAL DATA

### 1. Introduction

The emphasis in earlier reports on this program has been on design information for band-pass filters. Formulas and data have been presented for couplings between cascaded resonators inside cut-off metal tubes, and for loading of the end resonators by loops or probes connected to coaxial terminations.

During the past quarter attention was given to band-stop applications. A dielectric resonator coupled to the H field of a propagating transmission line or waveguide will cause a sharp rejection response at the resonator's resonant frequency. The case of a TEM-mode line consisting of a center rod or strip between parallel ground planes is especially interesting because of the ease of introducing and adjusting dielectric resonators. Therefore, this case was analyzed, resulting in a simple formula for the external Q of the resonator as loaded by the line. Experimental data demonstrated that the formula is sufficiently accurate for usual applications. Utilizing this information, several band-stop filters were designed. Experimental performance closely followed that predicted by theory.

Additional dielectric samples supplied by U. S. Army Electronics Laboratories have been measured. In several cases greater densities and dielectric constants than those of previous samples were observed. The correlation between density and dielectric constant was found to be consistent with the trend of earlier tests.

## 2. Band-Stop Filters

Dielectric resonators coupled to a propagating transmission line will exhibit band-stop (or band-rejection) characteristics. Far from resonance they will be loosely coupled to the line and will cause very small reflections. In the vicinity of resonance, however, a dielectric resonator will introduce a high peak of reflection loss. The bandwidth of this effect is determined by the degree of coupling of the resonator to the transmission line.

In the First Quarterly Report[1], a technique for measurement of the unloaded Q of dielectric samples was described in which the samples were used as band-rejection resonators. The resonators were mounted on polyfoam supports in WR-284 waveguide. During the course of these measurements, it was observed that very weak coupling was obtained when the axis of the disk resonator was parallel to the axis of the waveguide and near its center. Previous analyses during this program have shown that coupling is maximum when the magnetic-dipole axis of the resonator is parallel to the incident H field, and is zero when perpendicular. Since the $H_z$ component of the dominant $TE_{10}$ mode in rectangular waveguide is zero on the axis of the waveguide and maximum at the side walls, the observed behavior is to be expected. When the axis of the resonator is parallel to the transverse H field of the waveguide, maximum coupling occurs at the center and minimum at the sides. Again, this is as expected from the transverse-H distribution function.

Typical values of external Q for dielectric resonators in a propagating waveguide are shown in Table 4-1.

In general, proper design of band-stop filters requires that resonators be coupled to the line at odd-quarter-wavelength intervals.

Table 4-1

EXTERNAL Q OF RESONATORS IN WR-284 WAVEGUIDE

Sample Size - 0.430" D x 0.220" L; $\epsilon_r \approx 97$

| Sample Orientation | Location | Resonant Frequency | 3-db Bandwidth | $Q_{ex}$ |
|---|---|---|---|---|
| Axial | Centered | - | negligible | |
| Axial | 0.170" off WG axis* | 3030 Mc | 0.92 Mc | 3300 |
| Axial | 0.420" off WG axis* | 3034 | 4.99 | 609 |
| Transverse | Centered | 3032 | 36.3 | 83.5 |

*Displaced toward side wall

Typically, $3\lambda_g/4$ spacings are needed to prevent excessive fringing-field coupling between resonators, which would degrade the rejection response. Therefore, the use of dielectric resonators in such a structure instead of external rejection cavities will not materially reduce the over-all length of a filter. However, dielectric resonators can make possible an over-all filter cross section the same as the waveguide itself, while offering high $Q_u$ values approximately equal to that of external waveguide cavities. Dielectric-resonator band-stop filters in waveguide appear to offer only a moderate volume reduction compared to conventional cavity-resonator structures without other important advantages.

In the case of a TEM-line rejection filter, the reduction in cross section can be very large when dielectric resonators are used in place of conventional resonators of equal $Q_u$. A length reduction is also possible if the center conductor is zig-zagged or wound in a helix. A TEM structure consisting of a rod or strip conductor between parallel planes is especially convenient for experimentation. The dielectric resonator can be machined to exhibit the desired resonant frequency and then inserted between the ground planes at the proper distance from the center conductor to provide the required coupling. The small size of the dielectric resonator and the absence of any extraneous coupling structure minimizes the problem of coupling between adjacent resonators. Finally, such resonators can be tuned by adjustments, which can be built into the structure in a very simple manner.

In the following sections, the coupling between dielectric resonators and several TEM-mode transmission lines is analyzed. Designs for band-stop filters are given and experimental results are presented. These show excellent agreement with the theoretically predicted performance.

## 3. Dielectric Resonator Adjacent to a Propagating TEM Line

### a. Formula for Slab Line Case

A dielectric resonator placed in the field of a propagating transmission line as shown in Figure 3-1 will be magnetically coupled to the line. For most effective coupling, the magnetic-dipole axis of the resonator should be in the direction of the H field of the transmission line. This is the case in Figure 3-1, where $m = m_y$ and $H = H_y$ at the center of the dielectric disk. At and near resonance, the disk couples an equivalent parallel-resonant circuit in series with the transmission line, producing a rejection response between the input and output ports as shown in Figure 3-2. The bandwidth at the 3-db insertion-loss points increases with coupling, and the peak of the insertion-loss curve increases both with coupling and with the unloaded Q, $Q_u$, of the resonator. The loaded Q, $Q_L$, is defined as

$$Q_L = \frac{f_o}{f^+_{3db} - f^-_{3db}} \qquad (3-1)$$

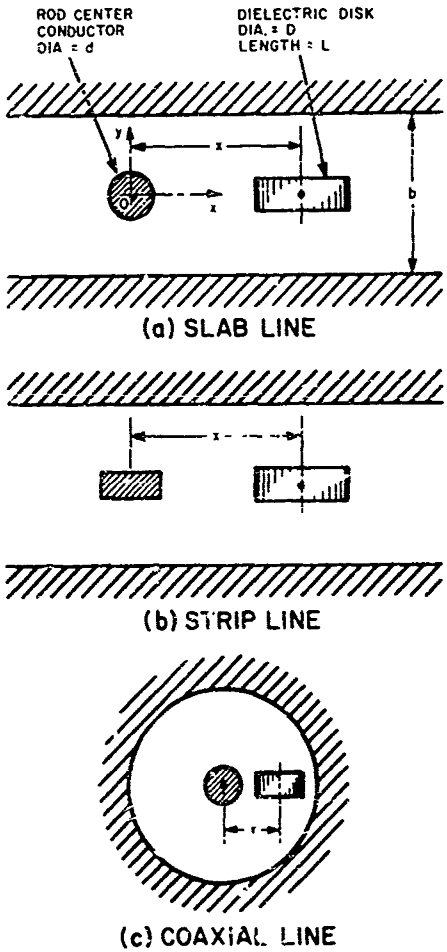



Figure 3-1. Dielectric Resonator Coupled to Various TEM-Mode Lines

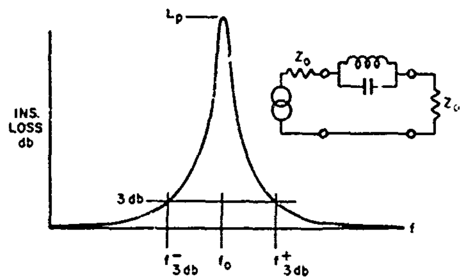



Figure 3-2. Insertion Loss Response and Equivalent Circuit for Configuration of Figure 3-1

If $Q_u = \infty$, $Q_L$ is equal to the external Q, $Q_{ex}$, since in that case the dissipation of resonator energy occurs entirely in the $Z_o$ terminations at the two ends of the transmission line. The usual relation between $Q_L$, $Q_u$, and $Q_{ex}$ applies, as follows.

$$\frac{1}{Q_L} = \frac{1}{Q_{ex}} + \frac{1}{Q_u} \qquad (3\text{-}2)$$

The formula for peak insertion loss $L_p$ versus $Q_u$ and $Q_L$ was given in the First Quarterly Report, page 21: [1]

$$L_p = 20 \log_{10}\left(\frac{Q_u}{Q_L}\right) \quad \text{db} \qquad (3\text{-}3)$$

A rigorous solution is not feasible for the case of a dielectric resonator in the field of a transmission line. A useful formula

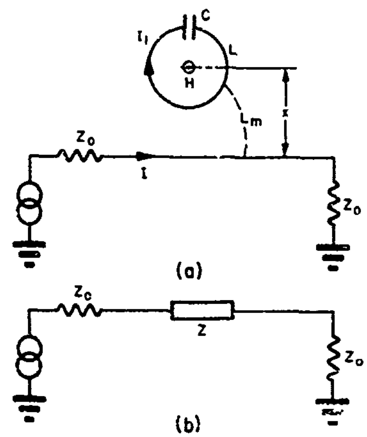



Figure 3-3. Equivalent Circuits Used in Analysis of Dielectric Resonator Coupled to TEM-Mode Line

may, however, be derived through the use of certain simplifying assumptions. The principal assumption is that the dielectric resonator may be replaced as in Figure 3-3 by an inductive loop tuned to resonance by a series capacitor, the stored energy and the magnetic-dipole moment being respectively the same for the two situations. This assumption was used successfully in the Second Quarterly Report in the derivation of a formula for the coupling-coefficient between two dielectric resonators.[2] A generalized formula applying to any kind of transmission line is derived below in paragraph (c) of this subsection. The general formula is then particularized for the slab-line configuration of Figure 3-1(a), yielding the following formula for external Q, $Q_{ex}$:

$$Q_{ex} = \frac{Z_o \lambda_o b^2}{30\pi^2 F} \sinh^2\left(\frac{\pi x}{b}\right) \tag{3-4}$$

where

$$F = \frac{\mu_o m_1^2}{2W_{m1}} \tag{3-5}$$

is a factor that is a function of the parameters of the disk. A simple but quite accurate approximation for F is given in the Third Quarterly Report, as follows:[3]

$$F = \frac{0.927 D^4 L \epsilon_r}{\lambda_o^2}, \quad 0.25 \le L/D \le 0.7 \tag{3-6}$$

In the useful L/D range of 0.25 to 0.7, this is within 2% of a more complex expression given in the Second Quarterly Report.

Equation 3-4 applies approximately to the strip-line cross section in Figure 3-1(b). In the coaxial-line case of Figure 3-1(c), the following holds.

$$Q_{ex} = \frac{r^2 Z_o \lambda_o}{30F} \tag{3-7}$$

b. Comparison of Theoretical and Experimental Data

Figure 3-4 shows a comparison between curves computed from Eqs. 3-4 and 3-6, and points measured in a 50-ohm slab line. The key dimensions and other parameters are shown in the figure. In computing the theoretical curves, use was made of the measured values of resonant frequency for the two disks.

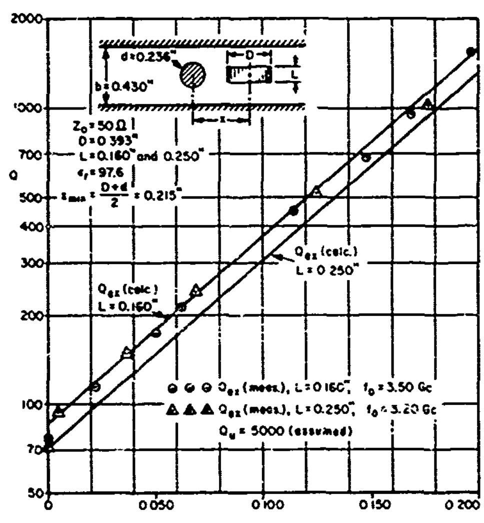



Figure 3-4. Comparison Between Theoretical and Experimental $Q_{ex}$ for a Dielectric Disk Coupled to a Propagating Slab Line

The agreement in Figure 3-4 is quite good, and is adequate for design purposes, but a minor anomaly exists. The two theoretical $Q_{ex}$ curves are parallel to each other and in the ratio of 1.2:1 for the disk lengths L = 0.160 and 0.250". The experimental points for these two cases, however, do not show any separation, and appear to define a single curve. The points fall mainly between the two theoretical curves, and appear to favor the upper curve.

The quantity actually measured was the total loaded Q, $Q_L$, defined in Eq. 3-1. In order to obtain $Q_{ex}$, Eq. 3-2 was used with an assumed value of $Q_u$. Previous data described in the Third Quarterly Report, page 24, shows these samples to have $Q_u$ values on the order of 7000 when measured in a large propagating waveguide.[3] In the slab-line configuration, the disk is in close proximity to the aluminum ground planes. Proximity of a dielectric resonator to a metal wall results in a degradation of $Q_u$. Data in the Third Quarterly Report, page 24, indicates $Q_u = 5000$ to be a reasonable expectation for this case. An error in the assumed value of $Q_u$ would have a negligible effect for $Q_{ex} << Q_u$, and only a moderate effect when $Q_{ex} = 0.3Q_u$, which is approximately the highest $Q_{ex}$ value appearing in Figure 3-4. In fact, any $Q_u$ value between 4000 and 7000 will yield very nearly the same $Q_{ex}$ data, and at the sensitive upper end of the curve $Q_{ex}$ will be affected by only ±8%.

c. Derivation of $Q_{ex}$ Formulas

In its effect on an external circuit, the resonant loop of Figure 3-3(a) is equivalent to a resonant dielectric object when their respective magnetic dipole moments and stored energies are equal. These quantities are as follows

$$m_1 = AI_1 \tag{3-8}$$

$$W_{m1} = \frac{1}{2} LI_1^2 \tag{3-9}$$

where A is the area of the loop and $I_1$ and L are its current and inductance. The loop couples an impedance $Z = jX$ in series with the line, as in Figure 3-3(b). Elementary circuit theory applied to Figure 3-3(a) yields the anti-resonant reactance function

$$X = \frac{Z}{j} = \frac{-\left(\omega L_m\right)^2}{\omega L\left(1 - \frac{\omega_o^2}{\omega^2}\right)} \tag{3-10}$$

where $L_m$ is the mutual inductance between the loop and the line, and $\omega_o^2 = 1/LC$. At $\omega_o$, X is infinite, and a rejection peak occurs.

A narrow-bandwidth approximation for X is as follows

$$X = \frac{-\left(\omega_o L_m\right)^2}{2\omega_o L\left(\frac{f-f_o}{f_o}\right)} \tag{3-11}$$

At the 3-db points,

$$X_{3db} = \pm 2 Z_o \tag{3-12}$$

and

$$\frac{f_{3db}^{\pm}}{f_o} = 1 \pm \frac{\left(\omega_o L_m\right)^2}{4\omega_o L Z_o} \tag{3-13}$$

Hence

$$Q_{ex} = \frac{f_o}{f_{3db}^{+} - f_{3db}^{-}} = \frac{2\omega_o L Z_o}{\left(\omega_o L_m\right)^2} \tag{3-14}$$

Next make use of the following relations for the voltage $V_1$ induced in the loop by I and by $dB/dt = j\omega_o\mu_o H$.

$$V_1 = j\omega_o L_m I \tag{3-15}$$

and

$$V_1 = j\omega_o\mu_o \iint_A \underset{\sim}{H} \cdot \underset{\sim}{da} \tag{3-16}$$

where integration is over the loop area A, and H is the magnetic field through A due to the transmission-line current I. If H is perpendicular to the loop area,

$$V_1 = j\omega_o\mu_o \iint_A H\, da \approx j\omega_o\mu_o HA \tag{3-17}$$

where in the latter expression, H is a mean value of H on the surface A, and is approximately equal to the value of H at the center of A.

Equations 3-15 and 3-16 give

$$\omega_o L_m = \frac{\omega_o\mu_o}{I} \iint_A \underset{\sim}{H} \cdot \underset{\sim}{da} = \frac{2\pi\eta}{\lambda_o I} \iint_A \underset{\sim}{H} \cdot \underset{\sim}{da} \tag{3-18}$$

since $\omega_o\mu_o = 2\pi\eta/\lambda_o$, where $\eta = 120\pi$ ohms is the characteristic impedance of free space. Equations 3-8 and 3-9 give

$$I_1 = \frac{m_1}{A} \tag{3-19}$$

$$L = \frac{2W_{m1}}{I_1^2} \tag{3-20}$$

Equations 3-18 — 3-20 may now be substituted in Eq. 3-14 to yield

$$Q_{ex} = \left(\frac{2W_{m1}}{\mu_o m_1^2}\right) \cdot \frac{\lambda_o Z_o I^2 A^2}{\pi\eta \left[\iint_A H \cdot da\right]^2} \approx \frac{\lambda_o Z_o I^2}{\pi F \eta H^2} \qquad (3\text{-}21)$$

The factor

$$F = \frac{\mu_o m_1^2}{2W_{m1}} \qquad (3\text{-}22)$$

has occurred in previous analyses on this program,[2,3,4] and is a function of the dimensional and electrical parameters of the dielectric resonator. A simplified formula for F is given in Eq. 3-6.

Equation 3-21 applies to a dielectric resonator in the H field of any TEM-mode line. (In fact, with proper normalization of $Z_o$ and I, it can also be applied to the case of a dielectric resonator in a propagating waveguide.) To apply Eq. 3-21 to a coaxial line, strip line, slab line, two-wire line, etc., it is merely necessary to evaluate the following

$$\frac{1}{IA} \iint_A \underset{\sim}{h} \cdot \underset{\sim}{da} \approx \frac{H}{I} \qquad (3\text{-}23)$$

for the specific cross section. The ratio H/I is a function of x and y in the transmission-line cross section. It may be determined by conformal mapping or other mathematical techniques.

In coaxial line, for example,

$$\frac{H}{I} = \frac{1}{2\pi r} \qquad (3\text{-}24)$$

where r is any radius between the inner and outer conductor, and H is circumferentially directed. Thus, in coaxial line (Figure 3-1c),

$$Q_{ex} = \frac{r^2 Z_o \lambda_o}{30F} \tag{3-25}$$

Slab line is an especially useful configuration for dielectric-resonator band-reject-filter design. The following formula has been shown to apply along the x-axis when d << b.

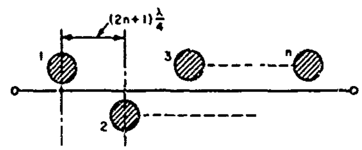
$$H_y = \frac{I}{2b \sinh \frac{\pi x}{b}} \tag{3-26}$$

The geometry is as in Figure 3-1. Note that for $\pi x/b << 1$, $H_y \approx I/2\pi x$, which agrees with Eq. 3-24. Also, for $\pi x/b \gg 1$, $H_y = (I/b)e^{-\pi x/b}$, which indicates a transverse attenuation constant of $\pi/b$ nepers or 27.3/b db, as should be expected for a slab or strip line.

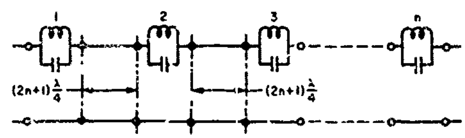
When Eq. 3-26 is substituted in Eq. 3-21, the formula given in Eq. 3-4 is obtained. The condition d << b that was placed on Eq. 3-26 is not especially stringent. Further analysis shows Eq. 3-26 to be valid within a few percent for $Z_o \geq 50$ ohms and $d \leq 0.$ [illegible]b.

4. Design of Band-Stop Filters in TEM Lines

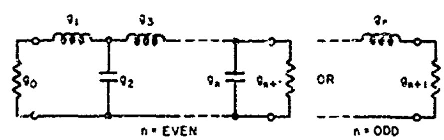
The design of band-stop (band-rejection) filters exhibiting prescribed insertion loss characteristics has been described by Young, et al[5,6] in terms of the elements of a low-pass prototype filter. For a filter having a narrow bandwidth, the external Q's of the individual resonators can be expressed directly in terms of the elements of the low-pass prototype filter and the parameters of the frequency transformation. In the circuit of Figure 4-1, the low-pass prototype



(a) DIELECTRIC RESONATOR BAND STOP FILTER



(b) EQUIVALENT CIRCUIT FOR (a)



(c) LOW-PASS PROTOTYPE OF (b)

Figure 4-1. Slab Line Band Stop Filter

structure is realized by dielectric resonators coupled in series with the transmission line at intervals equal to an odd multiple of a quarter wavelength. Young defines a susceptance slope function[5,6]

$$b_i = \frac{\omega_o}{2} \cdot \frac{dB_i}{d\omega}\bigg|_{\omega = \omega_o} \qquad (4\text{-}1)$$

where $B_i$ is the susceptance of the ith resonator. For the constant-admittance line structure of Figure 4-1, it has been shown that[5,6]

$$\frac{b_i}{Y_o} = \frac{1}{\omega_1' w g_i} \qquad (4\text{-}2)$$

At the 3-db-bandwidth points of an individual resonator, the susceptance in series with the line is equal to $-Y_o/2$ or $+Y_o/2$, while at $\omega_o$ the susceptance is zero. Thus, dB is equal to $Y_o/2$ when $d\omega$ corresponds to half of the 3-db bandwidth. Then, from Eq. 4-1,

$$b_i = Q_{ex_i} \frac{Y_o}{2} \qquad (4\text{-}3)$$

where $Q_{ex_i} = \frac{\omega_o}{2d\omega}$ is the external Q of the ith resonator. Then, substituting Eq. 4-3 in Eq. 4-2, one obtains

$$Q_{ex_i} = \frac{2}{\omega_1' w g_i} \qquad (4\text{-}4)$$

where w is the normalized bandwidth corresponding to the low-pass prototype frequency $\omega_1'$ (see Figure 4-2).

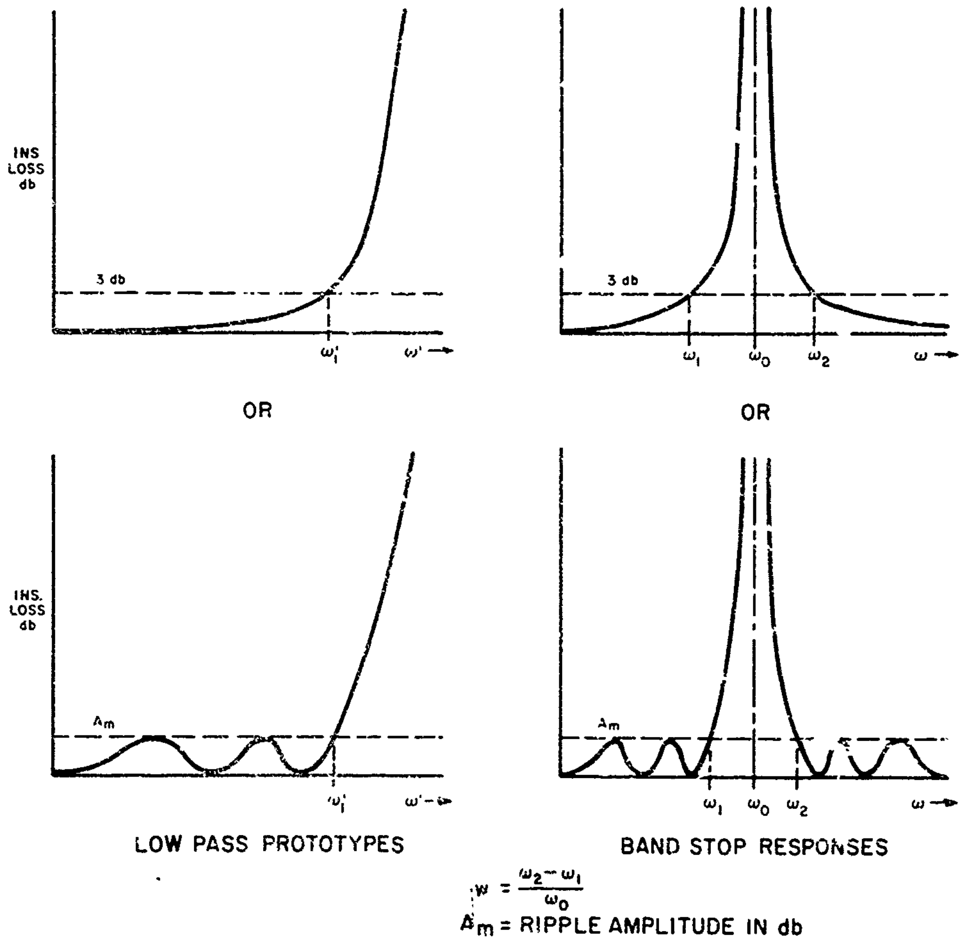



Figure 4-2. Ideal Filter Characteristics

A three-resonator band-stop filter was designed to exhibit a 3-db rejection bandwidth of 17.3 Mc at 3394 Mc with a 0.01-db ripple pass-band characteristic. (Equal ripple bandwidth is theoretically 32.5 Mc in this case.) From Eq. 4-4, and by use of tables of element values for the 0.01-db ripple case, it was determined that the end resonators should have external Q's of 331 and the center resonator should have an external Q of 214.

An experimental filter was constructed in a slab line, having 0.430" ground-plane spacing and a center-conductor diameter 0.236". A shorting block, containing a 1/4" tuning screw, was mounted between the ground planes adjacent to each resonator. Three dielectric resonator samples were ground to 0.393" diameter. The height of each resonator was ground so that, when mounted in the slab line, it would resonate at approximately 3390 Mc. The end resonators had heights of 0.240" while the center resonator height was 0.230". Fine tuning was accomplished by means of the tuning screws. A photograph of the experimental filter structure, with the top ground plane removed, is shown in Figure 4-3. Note that adjacent resonators are placed on opposite sides of the center conductor to minimize direct coupling between resonators. In addition, shorting posts were placed between the ground planes surrounding the resonators. However, later test results demonstrated that performance was not affected when the shorting posts were removed. It was concluded that direct coupling between resonators and the excitation of parallel-plate modes in the slab line were not sufficiently strong to be of concern. A substantial reduction in width would, of course, be feasible in Figure 4-3.

Data was taken to determine the external Q of each resonator as a function of center-conductor-to-resonator spacing. A value of $Q_u = 5000$ was assumed in obtaining $Q_{ex}$ from the measurements of $Q_u$. Theoretical values of $Q_{ex}$ were computed, by means of Eq. 4-4, for prescribed filter characteristics. The resonators were then placed on the slab line at $3\lambda/4$ intervals and with spacings from the

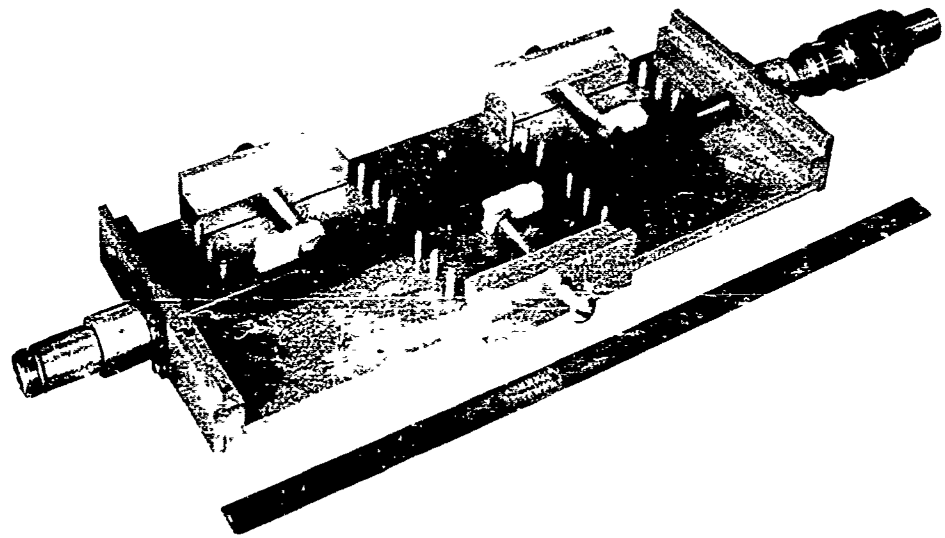


Figure 4-3. Photo of Slab Line Band Stop Filter

center conductor to yield the required resonator $Q_{ex}$ values. Each resonator was tuned to the prescribed center frequency by means of the tuning screw. Minor adjustments were required in the positions of the resonators and the tuning screws in order to obtain the correct filter performance.

Figure 4-4 compares the experimental performance of a three-resonator, 0.01-db ripple filter with a 17.3-Mc 3-db rejection band-width to the theoretical characteristics. The external Q of each resonator was then determined by measuring the final position of the resonator in the filter assembly. These values of $Q_{ex}$, neglecting the effects of the tuning screw, are compared to the theoretical values.

| | $Q_{ex}$ (Theoretical) | | | $Q_{ex}$ (Experimental) |
|---|---|---|---|---|
| | 3 db Bandwidth | | | |
| | 17.3 Mc | 18.3 Mc | 18.9 Mc | |
| Input Resonator | 331 | 312 | 303 | 305 |
| Center Resonator | 214 | 202 | 196 | 212 |
| Output Resonator | 331 | 312 | 303 | 323 |

It can be seen that relatively small changes in $Q_{ex}$ will affect the bandwidth of the filter. Such changes can be introduced by the tuning screws. To demonstrate this, the position of the resonators was left unchanged and the tuning screws were readjusted to provide a wider bandwidth. The filter characteristics that were obtained are compared to the theoretical response of a 0.01-db ripple filter with an 18.9 Mc 3 db bandwidth in Figure 4-5. It was noted that the insertion loss as determined from transmission measurements was approximately 1 db greater than the insertion loss due to reflections at the theoretical 3-db point. This data compared well with a calculated value, (using a formula derived by Young,[4,5]) of approximately 0.9 db loss due to dissipation at this point.

Similar agreement between theoretical and experimental results was obtained for a two-resonator, 0.1-db ripple filter with a 9-Mc, 3-db rejection bandwidth and a three-resonator, 0.1-db ripple filter with a 24-Mc, 3-db rejection bandwidth.

Measurements were also made to determine the effect of a tuning screw upon the characteristics of a single resonator. It was observed that from zero insertion of the screw to the point of contact the resonant frequency increased by approximately 10 Mc. This was accompanied by an increase of approximately 0.7 Mc in the 3-db bandwidth of the resonator when it was tightly coupled to the transmission line ($Q_L$ = 215) and 0.4 Mc when the resonator was more loosely coupled to the line ($Q_L$ = 385).

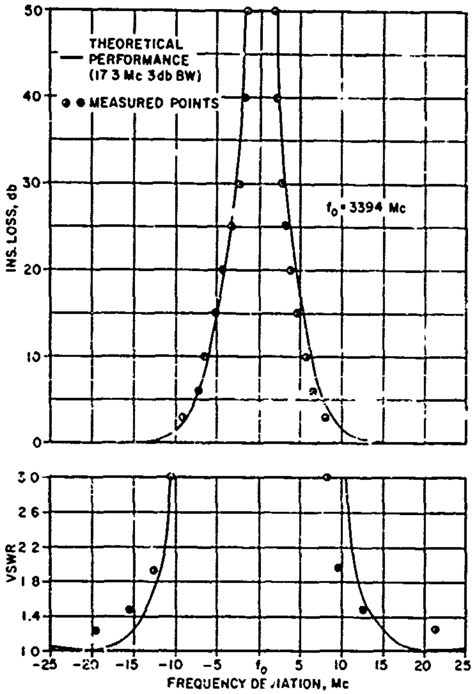



Figure 4-4. Response of 3 Resonator Band Stop Filter in Slab Line, Alignment 1

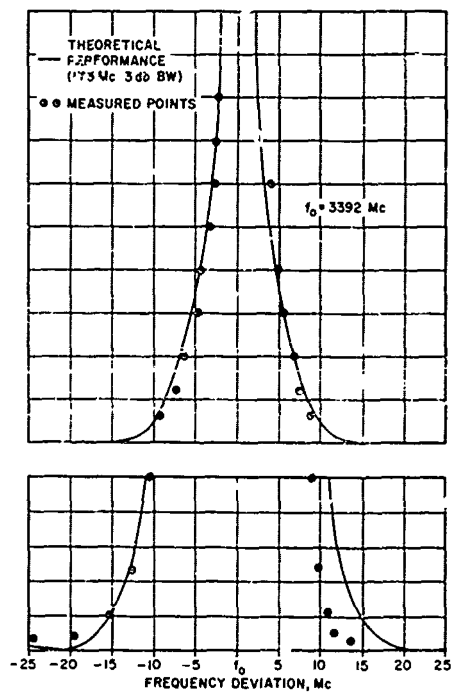



Figure 4-5. Response of 3 Resonator Band Stop Filter in Slab Line, Alignment 2

It has therefore been demonstrated that band stop filters using dielectric resonators coupled to TEM lines can be designed and constructed. Analytic techniques, or a combination of analytic and experimental techniques, can be employed to determine the size and location of the resonators within the TEM line. Sufficient accuracy is obtained, for most applications, so that only simple tuning and alignment techniques need be employed in adjusting the filter for its prescribed performance.

## 5. Dielectric Constant Measurements

Ten samples of dielectric materials have been received from U. S. Army Electronics Laboratories. Seven of these samples were of $TiO_2$, one was barium titanate, one a mixture of barium titanate, and one was $PbZrO_3$. The latter three samples did not exhibit any resonances and therefore no data were obtained. Of the remaining seven samples, one was broken in transit and could not be tested. Data for the remaining six are shown in Table 5-1. The correlation between sample density and dielectric constant observed in earlier tests was borne out by the latest samples. This is illustrated in Figure 5-1 where some of the earlier $TiO_2$ samples are included for comparison.

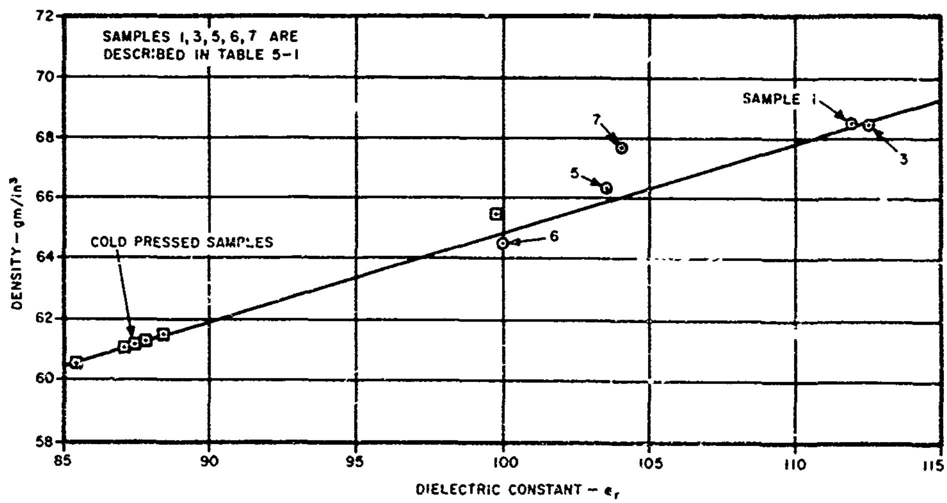



Figure 5-1. Dielectric Constants of $TiO_2$ Samples as a Function of Sample Density

TABLE 5-1

DIELECTRIC MATERIALS

| Sample | Firing Process | $\epsilon_r$ | Results Density gm/in$^3$ | Q |
|---|---|---|---|---|
| 1. $TiO_2$ (Baker's) | Hot pressed, 5000 psi, 2260°F, 20 min. hold time.<br>2000°F in $O_2$ for 12 hours. | 111.9 | 68.6 | 5,700 |
| 2. R-200 $TiO_2$ (Dupont) | Hot pressed, 5000 psi, 2250°F, 20 min. hold time.<br>2000°F in $O_2$ for 12 hours. | Broken sample; inadequate for test. | | |
| 3. R-200 $TiO_2$ | Hot pressed, 5000 psi, 2300°F, 20 min. hold time.<br>2000°F in $O_2$ for 12 hours. | 113.5 | 68.5 | 9,500 |
| 4. $TiO_2$ (Nat'l Lead - MP-1949) | Hot pressed, 5000 psi, 2250°F, 20 min. hold time.<br>2000°F in $O_2$ for 12 hours. | 86.0 | 47.8 | * |
| 5. $TiO_2$ (Nat'l Lead - MP-1949) | Hot pressed, 5000 psi, 2260°F, 20 min. hold time.<br>2000°F, in $O_2$ for 12 hours. | 103.5 | 66.4 | 11,800 |

*No Q data taken. Resonant frequency in band rejection mode of operation inconsistent with those of other samples and those observed during radial line dielectrometer measurements. Further measurements indicated significant anisotropy in this sample.

TABLE 5-1 (Cont'd)

| Sample | Firing Process | $\epsilon_r$ | Results Density $gm/in^3$ | Q |
|---|---|---|---|---|
| 6. TiO (Nat'l Lead - MP-1949) | Hot pressed, 5000 psi, 2250°F, 20 min. hold time.<br>2000°F in $O_2$ for 12 hours. | 99.9 | 64.5 | 11,000 |
| 7. $TiO_2$ (Baker's) | Reg. Fired, 2600°F two hours. | 104.00 | 67.8 | 5,500 |
| 8. $Bi_4Ti_3O_{12}$ | | Did not resonate. | | |
| 9. $Bi_4Ti_3O_{12}(.60)$ $TiO_2(.40)$ | Hot pressed | Did not resonate. | | |
| 10. $PbZ_rO_3$ (TAM Lot No. 1) | | Did not resonate. | | |

## SECTION V

## CONCLUSIONS

The use of dielectric resonators in TEM-mode transmission line to achieve band-stop filters has been successfully demonstrated. A theoretical analysis of $Q_{ex}$ has resulted in a simple formula that agrees well with measured data. Application of this formula to several experimental band-stop filters in a slab-line cross section yielded good correlation between computed and experimental insertion-loss response.

Various $TiO_2$ samples were measured. Several had dielectric constants as high as 113.5. These samples had been hot pressed at very high pressures and temperatures, yielding in most cases higher densities than previous samples. The $Q_u$ values varied from 5700 to 11,800.

## SECTION VI

## PROGRAM FOR NEXT INTERVAL

Techniques will be considered for achieving tight end loading between external transmission lines and dielectric-resonator band-pass filters. Rectangular waveguide loading of resonators in both the axial and transverse orientations will be considered. The band-pass configuration of axially oriented resonators in a cut-off circular tube will be investigated theoretically and experimentally.

## SECTION VII

## LIST OF REFERENCES


1. S. B. Cohn and C. W. Chandler, "Investigation of Microwave Dielectric-Resonator Filters," First Quarterly Report on Contract DA-36-039-AMC-02267(E), 1 July 1963 to 30 September 1963, Rantec Corp., Project No. 31625.

2. S. B. Cohn and K. C. Kelly, "Investigation of Microwave Dielectric-Resonator Filters," Second Quarterly Report on Contract DA-36-039-AMC-02267(E), 1 October 1963 to 31 December 1963, Rantec Corp., Project No. 31625.

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5. P. S. Carter, Jr., L. Young, G. L. Matthaei, and E. M. T. Jones, "Microwave Filters and Coupling Structures," Third Quarterly Report, Stanford Research Institute, 1 July 1961 to 30 September 1961.

6. L. Young, G. L. Matthaei, and E. M. T. Jones, "Microwave Bandstop Filters with Narrow Stop Bands," IRE Trans on MTT, Vol MTT-10, pp. 416-427, Nov. 1962.

## SECTION VIII

## IDENTIFICATION OF KEY TECHNICAL PERSONNEL

| | Hours |
|---|---|
| Dr. Seymour B. Cohn<br>Specialist | 148 |
| Mr. Eugene N. Torgow<br>Staff Engineer | 165 |
| Mr. Kenneth C. Kelly<br>Senior Engineer | 100 |
| Mr. Richard V. Reed<br>Engineer | 62 |
| Mr. Howard V. Stein<br>Junior Engineer | 52 |

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Additional dielectric samples have been measured. Among the samples tested are several that are significantly more dense than earlier samples. These dense samples exhibited dielectric constants as high as 113. The quality of these samples from the point of view of Q was found to be comparable to the samples tested previously

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